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Coral reefs of the Red Sea — Challenges and potential solutions

M Fine
Bar Ilan University

Mine Cinar
Loyola University Chicago, mcinar@luc.edu

C R. Voolstra
University of Konstanz

A Safa
Skill Partners

B Rinkevich
Israel Oceanographic and Limnological Research, National Institute of Oceanography

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Authors
M Fine, Mine Cinar, C R. Voolstra, A Safa, B Rinkevich, D Laffoley, N Hilmi, and D Allemand

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Coral reefs of the Red Sea — Challenges and potential solutions

M. Fine [a,b,*], M. Cinar [c], C.R. Voolstra [d], A. Safa [e], B. Rinkevich [f], D. Laffoley [g], N. Hilmi [h], D. Allemand [h]

[a] The Mina and Everard Goodman Faculty of Life Sciences, Bar Ilan University, Ramat Gan, 5290002, Israel
[b] The Interuniversity Institute for Marine Sciences in Eilat, P.O.B. 469, Eilat 88103, Israel
[c] Loyola University Chicago, 82 N. Michigan Ave., Chicago, IL, 60611, USA
[d] Department of Biology, University of Konstanz, Universitätsstraße 10, 78457 Konstanz, Germany
[e] Skill Partners, 24 av Sidi Brahim 06130 Grasse, France
[f] Israel Oceanographic and Limnological Research, National Institute of Oceanography, Tel Shikmona, PO Box 8030, Haifa 31080, Israel
[g] World Commission on Protected Areas, IUCN (International Union for Conservation of Nature), 28 rue Mauverney, CH-1196 Gland, Switzerland
[h] Centre Scientifique de Monaco, Monaco, MC 98000, Monaco

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ABSTRACT

The Red Sea is a unique body of water, hosting some of the most productive and diverse coral reefs. Human populations along coasts of the Red Sea were initially sparse due to the hot and arid climate surrounding it, but this is changing with improved desalination techniques, accessible energy, and increased economic interest in coastal areas. In addition to increasing pressure on reefs from coastal development, global drivers, primarily ocean acidification and seawater warming, are threatening coral reefs of the region. While reefs in southern sections of the Red Sea live near or above their maximum temperature tolerance and have experienced bleaching events in the recent past, coral reefs in northern sections are considered a coral reef refugia from global warming and acidification, at least for the coming decades. Such differential sensitivities along the latitudinal gradient of the Red Sea require differential solutions and management. In an effort to identify the appropriate solutions to conserve and maintain resilience of these reefs along a latitudinal gradient, we used a SWOT analysis (strengths/weaknesses/opportunities/threats) to frame the present situation and to propose policy solutions as useful planning procedures. We highlight the need for immediate action to secure the northern sections of the Red Sea as a coral reef climate change refuge by management and removal of local stressors. There is a need to strengthen the scientific knowledge base for proper management and to encourage regional collaboration on environmental issues. Based on scientific data, solutions such as marine protected areas, fishing regulation, and reef restoration approaches were ranked for five distinct latitudinal sections in the Red Sea and levels of interventions are recommended.

1. Introduction

Humans occupied the Red Sea African coastline and made a living of its resources as early as 125Kyr ago, in the Stone Age (Walter et al., 2000). Human populations dispersed along the Red Sea coast, to the Levant basin and crossed to Arabia when sea-level low-stands (Gvirtzman et al., 1977) permitted crossing during glacial maxima (Bailey, 2010). However, the Red Sea populations remained sparse for millennia due to the hot and arid surrounding climate. When the Arabia Felix expedition in the 1760s explored the Red Sea (Hansen, 1962), coastal populations were very scarce. The regional demography changed with developing maritime transportation; particularly following the opening of the Suez Canal in 1869, with a dramatic increase in commerce between the Indo-Pacific and Europe. Improved desalination techniques, accessible energy, and increased economic interest in coastal areas encouraged local population growth through high birth rates and immigration to the coastal areas. While the entire population of the Red Sea countries exceeds 150 million people (Table 1), most of the inhabitants, to date, live inland or along the Mediterranean coast and only a fraction, presently reaching about 6 million residents, along the Red Sea coast (reviewed in Hinrichsen, 1999).

Cities (primarily port cities) such as Djibouti, Massawa, Al Hodeidah in the southern section, Jeddah (4 million people at present) and Port Sudan in the central section, and Safaga and Hurgada in the north section are rapidly developing. Eilat and Aqaba in the northernmost section of the Gulf of Aqaba have doubled in population size within a couple of decades, increasing their coastal footprint (Gradus, 2001). The total population of Egypt (nearly 100 million people in 2018) is localized primarily along

* Correspondence to: Bar Ilan University, The Interuniversity Institute for Marine Sciences in Eilat, P.O.B. 469, Eilat 88103, Israel .
E-mail address: maoz.fine@biu.ac.il (M. Fine).

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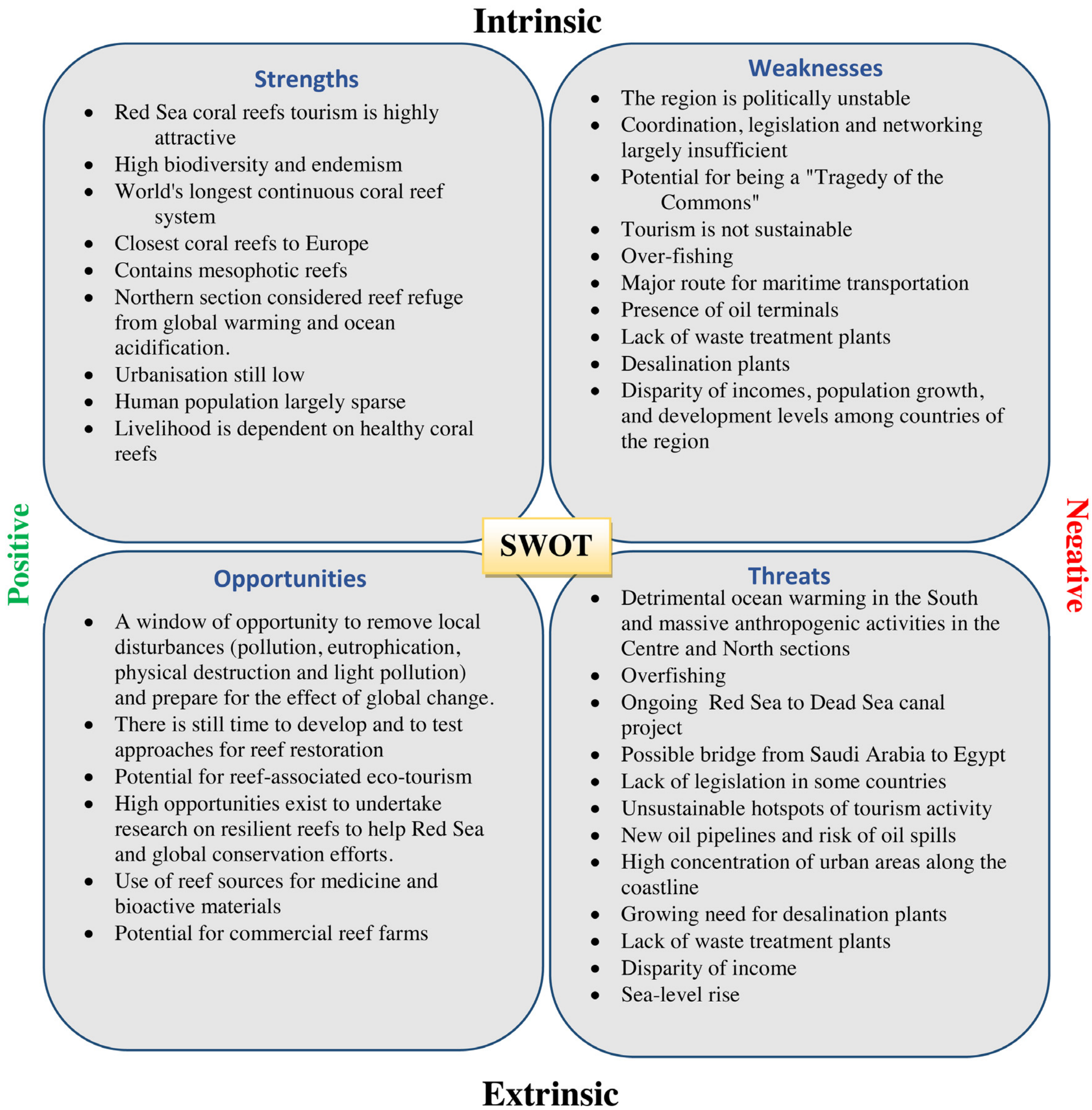

Fig. 1. SWOT (Strengths/Weaknesses/Opportunities/Threats) analysis diagram, representing the main factors considered for sustainability of the Red Sea Reefs.

the Nile River and is predicted to reach nearly 120 million people by 2030. This is an immense population growth with far reaching demographic implications (Ghanem, 2018) which may stretch out, all the way to the Red Sea.

The Red Sea is a unique body of water, hosting some of the most productive and richest coral reef ecosystems with coral reef framework along its entire coastline (DiBattista et al., 2016; Riegl et al., 2012). Clear blue water of the Red Sea and profusion of life, as well as its proximity to Europe have always been a source of attraction to generations of explorers and naturalists (reviewed in Berumen et al., 2013; Head, 1987), who acknowledged the high diversity of these reefs (Stehli and Wells, 1971) and their high endemism (Ormond and Edwards, 1987). DiBattista et al. (2016) reported 365 scleractinian coral species from the Red Sea including 19 (5.5%) endemic species.

Scleractinian, reef-building corals are the foundation species of the coral reef ecosystem. The reef framework provides shelter to thousands of fish and invertebrate species. Corals' obligate relationship with endosymbiotic dinoflagellates (family *Symbiodiniaceae*, (LaJeunesse et al., 2018)) form the base of a complex food web permitting a huge diversity of life in typically nutrient-poor tropical marine zones. Whilst the coral animal also feeds heterotrophically on zooplankton, photosynthates translocated from symbiont to coral host provide up to 95% of the coral's energetic intake (Muscatine, 1990) and facilitate rapid growth (skeleton deposition and tissue formation) and high productivity. Precipitation of calcium carbonate skeletons gives rise to the structural complexity of the reef itself. However, this coral-dinoflagellate symbiosis is sensitive to environmental changes such as variations in sea surface temperature (SST) and pH (Hoegh-Guldberg et al., 2007) as well as to land-based pollution originating from human activities (Fabricius, 2005; Wooldridge, 2009).

Over 64% of the world's coral reefs are located in developing countries with near shore dense populations (Pascal et al., 2016). While shores of the Red Sea are still not densely populated, the population is growing rapidly and being a narrow body of water, it exposes Red Sea fringing reefs to land-based disturbances in addition to the global threats (warming and acidification). Future population growth and urbanization in the region may increase human-reef interactions and conflicts.

The objective of this study is to highlight environmental, social, and economic aspects of coral reefs in the Red Sea in order to determine their strengths, weaknesses, opportunities, and threats (SWOT) towards better resource management that will warrant coral reefs' sustainability.

2. Material and methods

Data on the current status of reefs in the region was mined primarily from regional reports (PERSGA) and international reports (ReefBase, 2018; Wilkinson, 2004).

For the Ocean Data View chart, datasets from ReefBase and Chaidez et al. (2017) for temperature were used. Light pollution data was extracted from the dark site finder (Cinzano et al., 2001). In an effort to identify the appropriate solutions to maintain resilience of Red Sea coral reefs, we have performed a strengths, weaknesses, opportunities, and threats (SWOT) analysis as a useful planning procedure. SWOT is typically a strategic planning tool used to evaluate the strengths, weaknesses, opportunities, and threats to a project. It involves specifying the objective of the project and identifying the internal and external factors that are favorable and unfavorable to achieving that objective. The strengths and weaknesses usually arise from within an organization and the opportunities and threats from external sources. We consider the Red Sea coral reefs an entity and our common goal is to maintain it as a healthy functional and productive ecosystem conserving its ecological services.

Maximum temperature used to estimate thermal stress along a south-north gradient is the maximum monthly mean (MMM) based on long-term temperature records for each section of the Red Sea (Osman et al., 2018). The theoretical bleaching threshold of 1–2 degrees Celsius above the MMM is based on observations and experimental data (Hoegh-Guldberg et al., 2007). We consider the threshold to be the same across Red Sea sections based on the assumption that northern Red Sea corals underwent selection towards thermally resilient genotypes upon entering the Red Sea from the Gulf of Aden (Fine et al., 2013).

3. Results

A total of 9 Strengths, 10 Weaknesses, 6 Opportunities, and 12 Threats were identified for the Red Sea (Fig. 1). Among the Strengths, we highlight the first four items as strongest and most unique for the Red Sea: touristic attractiveness, high biodiversity, longest reef ecosystem (taking into account both eastern and western banks of the Red Sea) and closest reefs to Europe.

Weakness items were valued equally although it is obvious that, had the first three weaknesses (political instability, lack of coordination, and potential "tragedy of the commons") been resolved, all other items would be manageable and mitigation would be an option. We have identified unique opportunities in the Red Sea: rich natural resources with coral reefs being most productive; a stockpile of resources of monetary value. Reefs of the northern Red Sea offer a window of opportunity to "prepare" for and inform on future scenarios of environmental change and assure sustainability of reefs in the face of the planned urbanization and climate change in the region. While reefs of the world are dying from global warming, the northern Red Sea reefs have bought time for response to climate change scenarios, as described below.

An alarming number of threats put coral reefs of the Red Sea at risk (Table 2). Among these, global threats (warming and acidification) are of special concern but since Red Sea countries have only contributed about 5% to world CO_2 emissions, there is little that can be done to help significantly reduce the effect of climate change (Frölicher et al., 2013). Yet, local disturbances, which reduce the resilience of coral reefs to global stress, are where major opportunities lie as they can be minimized with proper planning and policies. We identify immediate threats such as waste discharge

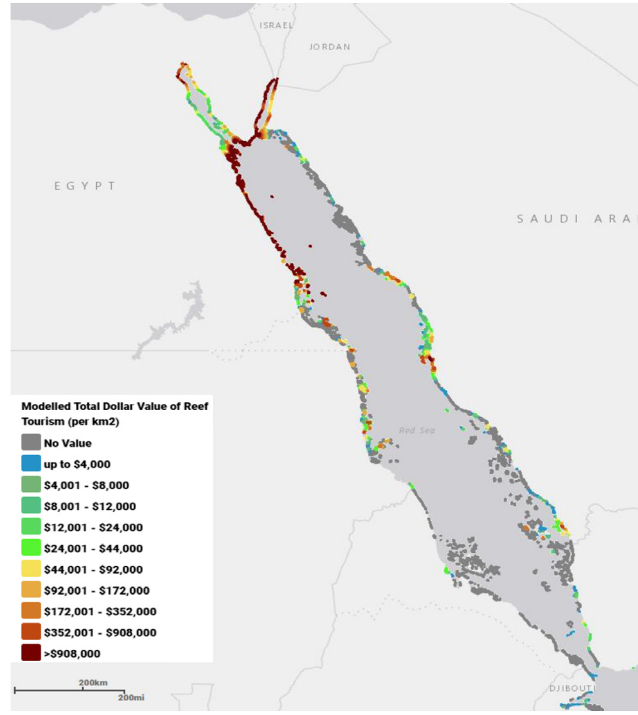

Fig. 2. Value (US$) of coral reefs for tourism in the Red Sea, highlighting hotspots of reef tourism in the central and northern Red Sea (Nature Conservancy, ocean wealth mapping http://maps.oceanwealth.org/).

and overfishing, which will have to be dealt with by enforcing existing rules and regulations. Long term threats include urbanization and population growth in an arid area in proximity to reefs. This can be circumvented if science-based planning and policies are developed.

3.1. Strengths

High biodiversity serves as a stockpile of potential food sources, marine natural products, and tourism opportunities. Marine natural products are bioactive metabolites present in many marine organisms that serve as agents against predators, fight diseases, and prevent the fouling and overgrowth by other organisms. As such, many of these compounds act as a prolific source of life-saving drugs and functional ingredients. While 80 percent of all life forms exists only in the oceans, most of the natural products identified to date are from terrestrial sources. It is estimated that less than 10 percent of coral reef biodiversity is known, and only a small fraction of the described species have been explored as a source of biomedical compounds (Bruckner, 2002). The Red Sea was found exceptionally rich of bioactive natural compounds with the coasts at Hurghada, Egypt and the Gulf of Eilat, Israel being the richest (El-Ezz et al., 2017). Various biological activity was recorded in hundreds of compounds isolated from Red Sea organisms including cytotoxic, antiproliferative, antiviral and anti-inflammatory activities (El-Ezz et al., 2017; Kremb et al., 2017; O'Rourke et al., 2016, 2018).

Reef-associated tourism alone is a major income for some Red Sea countries (Fig. 2). The Red Sea is one of the world's major tourist destinations. So far, coastal tourism has been concentrated along Egypt's eastern coastline, with a contribution of over 3.5% to Egyptian GDP (Hilmi et al., 2012). This is about to change with Saudi Arabia's Vision 2030 economic plan that seeks to diversify the kingdom's economy and reduce its reliance on revenues from oil (Fattouh and Sen, 2016; Gazette, 2016). Tourism, including coastal

Table 1
Coastline and socioeconomic data on the eight Red Sea countries. East coast from south, then west coast from south. Source: World Bank Data (https://data.worldbank.org/country), Population Reference Bureau 2018 (http://www.worldpopdata.org/map). GDP = gross domestic product. MPA = marine protected area.

	Yemen	Saudi Arabia	Jordan	Djibouti	Eritrea	Sudan	Egypt	Israel
Coastline in the Red Sea (km)	700	2000	26	314	2234	853	1600	14
Population total 2018 (million)	28.9	33.4	10.2	1	6	41.7	97	8.5
Population 2030 (million)	36.8	39.3	12	1.1	6.8	56.8	120.8	10.8
Population 2050 (million)	48.3	44.9	13.4	1.3	8.9	88.1	166.5	14.4
Rate of natural increase (%)	2.5	1.4	2.1	1.5	2.3	2.7	2.1	1.6
GDP (US$) Billion	27.3	646	39	2.0	2.6	96	253.25	373.75
CO_2 emissions (metric tons per capita)	0.86	19.5	3.0	0.8	0.13	0.3	2.2	7.8
Fisheries (metric tons)*	160,000	98,130	1,758	2,012	4,000	37,508	1,518,944	22,933
MPAs (% of territorial waters)	0.5	2.5	35.6	0.2	0	0	5.0	0.3

tourism. is considered the most promising part of the kingdom diversification plan, given the long coast and many attractive coral reefs along this coast.

The northern Red Sea has experienced the greatest increase in SST between 1950 and 2006 (Raitsos et al., 2011), yet only sporadic thermal bleaching has been reported in the Gulf of Aqaba (GoA; Loya, 2004). The GoA, at the northernmost extent of the Red Sea, has specifically been identified as a potential coral refuge to sea temperature rise (Fine et al., 2013; Osman et al., 2018). This region has also remained relatively unaffected by the current 3-year global bleaching event (Hughes et al., 2018), while being highly impacted by various anthropogenic activities (Loya, 2004). Multiple coral species show far above average physiological thermal tolerance in experimental exposures (Bellworthy and Fine, 2017; Fine et al., 2013; Krueger et al., 2017; Osman et al., 2018). The source of the thermal tolerance is hypothesized to be due to the recent geographical and hydrological history of the Red Sea since the last glacial maximum (Fine et al., 2013). During the last glacial maximum (20,000 years BP) sea level in the Red Sea was ca. 120 m lower (Siddall et al., 2003) reducing the basin's connection to the Gulf of Aden to a 6 km wide sill less than 20 m deep. At this time, high temperatures and high salinity extirpated coral species in the Red Sea (reviewed in Casazza, 2017). As global sea levels rose again, the vast majority of recolonization of the Red Sea occurred through the straits of Bab el Mandab and into the warm water in the Southern Red Sea (ca. 36 °C in summer). This presented a thermal barrier only permitting the northward movement of corals capable of withstanding high temperatures (Fine et al., 2013). Now settled in the Gulf of Aqaba, these corals live nearly 5–6 °C below their ancestral thermal maximum. Lastly, recent work on corals from the Persian/Arabian Gulf suggest that increased salinity, as found in the northern Red Sea in comparison to the southern Red Sea, might also be a factor that can increase stress resilience of coral holobionts by means of osmoadaptation (Gegner et al., 2017; Ochsenkühn et al., 2017). This is further supported by a recent study by Osman et al. (2018), which shows that thermal refugia against coral bleaching exist throughout the entire northern Red Sea.

There is growing empirical evidence to support the northern Red Sea refuge hypothesis. Gulf of Aqaba corals are physiologically resilient to up to 6 °C above local maximum summer mean temperatures (Bellworthy and Fine, 2017; Fine et al., 2013; Grottoli et al., 2017; Krueger et al., 2017). Unlike corals from other regions, corals within these experiments displayed little if any bleaching signs and, in some cases, showed improved performance with increased temperature (Krueger et al., 2017). A 1500 km latitudinal transect along the eastern Red Sea has revealed that there is a common optimum temperature for maximum calcification at 28–29 °C (Al-Sofyani and Floos, 2013; Sawall et al., 2015). This commonality suggests a shared ancestry and that this population has not adapted to local scale temperatures which vary by ca. 6–7 °C over the Red Sea latitudes within the same season.

Some studies reveal no structural differentiation of coral reef organisms in the Red Sea (Roberts et al., 2016; Sawall et al., 2015). Robitzch et al. (2015) showed no genetic separation of the common reef-building coral *Pocillopora verrucosa* over an 850 km stretch of the Red Sea, suggesting that there is panmixia and wide larval dispersal. In contrast, Maier et al. (2005) showed in northern Red Sea populations of *Seriatopora hystrix* a moderate genetic differentiation among populations over 650 km distance, as well as considerable heterozygote deficits and above all, have revealed isolation by distance effects on a small geographic scale of less than 20 km, indicating limited dispersal of larvae. Similar contrasting results for population genetics parameters were recorded for soft corals. While observations on *Heteroxenia fuscescens,* Fuchs and collaborators (Fuchs et al., 2006) did not reveal any genetic structure characteristic to a specific location, indicating extensive gene flow among specimens inhabiting the northern Gulf of Aqaba. In addition, Barki and colleagues (Barki et al., 2000) uncovered small-scale patchiness in the genetic structure of the shallow water soft coral *Parerythropodium fulvum fulvum.* Taken together, the current experimental evidence is ambiguous and large-scale studies using genome-wide methods (such as RAD-Seq) may confirm whether coral populations are largely connected across the spread of the Red Sea.

3.2. Weaknesses

Land and sea-based aquaculture is a growing industry in the Red Sea with an increasing demand for fish and shellfish despite the potential environmental negative effects that these farms may have. A long debate over fish farm effects on the coral reef of Eilat (Loya et al., 2004; Rinkevich, 2005) resulted in removal of the farms in 2008. In Saudi Arabia, traces of the nutrient-rich (4 times the ambient local concentration) effluent from the Al Lith aquaculture facility was detected up to 8 km away from the farm (Hozumi et al., 2018) raising concerns as to its impact on nearby reefs. Hall et al. (2018) suggested that eutrophication may compromise resilience of *Stylophora pistillata* to ocean acidification and warming conditions in the Gulf of Aqaba. The authors also reported a shift in the coral microbial community in eutrophication conditions that may in turn affect the coral health. Mariculture in Egypt is still in its infancy (Hilmi et al., 2014), but is likely to develop quickly given the demand for fish, scarcity of water for land-based freshwater aquaculture, and scarcity of land along the coast (reviewed in Shaalan et al., 2018).

The growing population in the arid Red Sea region increases demand for water for domestic, agricultural, and industrial purposes and have motivated a bloom of seawater reverse osmosis desalination plants construction. The returned hot brine, released with chemicals (coagulants and antiscalants; (Belkin et al., 2017)) often have negative environmental impacts. In Egypt Mabrook (1994) reported coral mortality nearby a desalination plant but other reports of coral resilience to increased salinity are also known from the Red Sea (van der Merwe et al., 2014).

Oil pollution from oil terminals and pipeline bursts are an almost chronic stress in some areas of the Red Sea. Several oil spills

Table 2
Threats to coral reefs in the greater Red Sea showing the risk (+ low, ++ medium, and +++ High) in each section (South, Center, North, Gulf of Aqaba, and Gulf of Suez) based on amplitude and frequency.

Threat	Source	Consequences	RS section	Reference
Oil spills	Ship, oil terminals	Coral and planula larva mortality	High risk throughout	(Loya and Rinkevich, 1980)
Sewage discharge	Cities	Changes in bacterial communities, algal growth	S+++, C++, N++, GoA ++, GoS++	(El Sayed, 2002; Walker and Ormond, 1982; Ziegler et al., 2016; Gerges, 2002)
Eutrophication	Sea and land-based mariculture and aqua culture, phosphate terminals, sewage	Macro algae domination over coral	S+++, C+, N+, GoA+, GoS+	(Ziegler et al., 2016; Loya et al., 2004; Hozumi et al., 2018; Hall et al., 2018)
Hot brine, coagulants and antiscalants, toxins, hydrocarbons, heavy metals discharge	Desalination plants, power stations	Coral mortality, changes in microbial communities	S+, C+++, N+, GoA+, GoS+	(Belkin et al., 2017; Omar et al., 2014)
Herbicides	Coastal, public gardens and Golf courses	Coral bleaching and mortality	S+, C++, N++, GoA++, GoS+	(Jones, 2005)
Insecticides	Towns and cities	Coral and invertebrates mortality	S+, C+++, N++, GoA++, GoS+	(Markey et al., 2007)
Sun screen	Tourists resorts	Coral poisoning, reduced resilience to thermal stress	S+, C+++, N+++, GoA+++, GoS+	(DiNardo and Downs, 2018)
Diving, snorkeling and reef trampling	Tourism industry (resorts, diving centers)	Corals and coral reef physical destructions, mortality, impacts on reproduction	S+, C+, N+++, GoA+++, GoS++	(Gladstone et al., 2013; Hasler and Ott, 2008; Leujak and Ormond, 2008b; Zakai and Chadwick-Furman, 2002)
Light pollution	Cities and coastal compounds, roads	Disruption to Reproductive synchronization	S+, C+++, N+++, GoA+++, GoS++	(Kaniewska et al., 2015; Tamir et al., 2017; Cinzano et al., 2001)
Acoustic pollution	Marine transportation, marine motorized sport,	Disrupted navigation of larvae, deterring mega fauna	S++, C+++, N+++, GoA+++, GoS+++	(Holles et al., 2013; Vermeij et al., 2010)
Plastic waste and micro plastic	Cities, resorts, ocean dumping, currents	Toxicity of entire food web	S+, C+, N+++, GoA +++, GoS++	(Hall et al., 2015)
Overfishing	Artisanal and commercial fishing fleets	Algal dominance with lack of grazers	S+++, C+++, N+++, GoA+, GoS++	(Spaet and Berumen, 2015)
Coastal construction	Urbanization and coastal infrastructure	Alterations in flow dynamics and physical damage to reefs, sedimentation	S++, C+++, N+++, GoA+++, GoS++	(Burke et al., 2006; Rogers, 1990)
Mining	Metal mining along the RS fault	Sedimentation and heavy metal pollution	S+++, C+++, N+++, GoA+++, GoS+++	(Gissi et al., 2017)
Heavy metals	Towns and cities, sewage, marine constructions, oil pollution, mining	Coral and planula accumulation in marine biota, coral reproduction	S+++, C+++, N+++, GoA+++, GoS+++	(Ali et al., 2011; El-Moselhy et al., 2014; El-Sorogy et al., 2012; Idris et al., 2007)
Physical destruction	Divers, boats and ship, marine construction	Coral breakage and higher susceptibility to pathogens	S+++, C+++, N+++, GoA+++, GoS+++	(Zakai and Chadwick-Furman, 2002)
Anti-fouling	Boats and marinas, shipping yards	Toxicity, reproductive disorders	S+++, C+++, N++, GoA++, GoS+++	(Owen et al., 2002)
Introduced species	Mariculture industry, Ballast water, aquariums, habitats alteration	Community structure shifts	S+, C+, N+, GoA+, GoS+	(Albins and Hixon, 2008)
Microbial and viral infection	Human and non-human vectors, ballast water, mariculture	Coral disease and mortality	S+++, C+++, N+++, GoA+++, GoS+++	(Aeby et al., 2017; Hadaidi et al., 2018; Rosenberg and Ben-Haim, 2002)
Flash floods	Alteration in catchment and drainage	Coral mortality, introduction of toxins	S+++, C+++, N+++, GoA+++, GoS+++	(Katz et al., 2015) (Kahana et al., 2002)
Deep sea mining	Mining for metals in along the RS fault	Benthic communities decimation	S+, C+++, N+, GoA, GoS	(Nawab, 1984; Thiel et al., 2015)

were reported in 2016 nearby flourishing coral reefs of Egypt and a 200 tons oil spill in Aqaba was luckily cleaned before any damage to the reefs were recorded (The Jordan Times, Aug 24, 2016). An even greater threat are oil tankers, which may transport huge volumes of crude oil very close to coral reefs. In April 2018, an oil tanker was attacked by a missile off the coast of Yemen. The impact that such an incident may have on reefs of the entire region is troubling. A high residence time of approximately 200 years and therefore long flushing time makes the Red Sea highly sensitive to any pollutants.

Increasing marine transportation and associated ports expansion pose another conflict between regional development and environmental sustainability. For example, commercial activities in Eilat and Aqaba ports have increased dramatically in recent years (transport of goods, passengers and containers terminals, oil terminals, mineral export facilities, naval bases and marinas). Some damages to the reefs have resulted from direct dredging on the coast, increased sedimentation rates from constructions and road expansion, especially in port areas due to the expansion and relocation of the containers ports.

Overfishing in the Red Sea affects 55% of all coral reefs (Burke et al., 2011) with artisanal fishing being the most common practiced fishing method. Fishing of top predators, i.e. sharks, for the shark-fin trade is common in the central and southern sections (Spaet and Berumen, 2015; Spaet et al., 2016) and often leads to smaller populations of herbivorous fish which in turn results in macro algal proliferation and dominance over coral cover (Hughes et al., 2007). Furthermore, it was found that coral microbial communities change in overfished sites (Jessen et al., 2013) and this directly affects the coral holobiont health.

Light pollution is another consequence of the growing population and urbanization of the Red Sea coastline. The eastern bank of the Red Sea has a higher light pollution than the western bank and the entire Gulf of Aqaba is exposed to high to very high levels of light pollution (Cinzano et al., 2001). The light emitted from cities at night may influence biological processes such as synchronization of circadian clocks and hence coral spawning (Kaniewska et al., 2015). It may also affect vertical migration of demersal plankton, feeding patterns, and prey/predator visual interactions (Tamir et al., 2017). Acoustic pollution is yet another overlooked disturbance, although the impacts of underwater noise on marine mammals is known for a long time and recent studies show effects on coral reef fish (Holles et al., 2013) and coral larva settlement preference (Vermeij et al., 2010). The Red Sea serves heavy maritime transportation and closer to reefs there are fishing boats, speed boats, glass bottom boats, etc.

One factor that may have a dramatic influence on sea-land interactions in the Red Sea is sea level rise (SLR) with predictions for 0.35 m (RCP 2.6) to 0.6 m (RCP 8.5) rise by the year 2100 (IPCC, 2014). Its implication on tourism and national income may be severe. SLR may promote acceleration of coastal erosion as well as inundation of mangroves, wetlands, and coral reefs. Inundation of coastal areas may result in intrusion of saline water into aquifers, which in turn will require more desalination plants to satisfy the demand for water in this arid region. The waterline is likely to be closer to coastal oil and chemical industries and even hotels, putting the nearby reefs at risk of pollution. In some countries, such as in the Gulf of Aqaba, mountains make it difficult for the population and industry to retreat landward. As coral reefs extend along the entire coast of the Red Sea and supply local populations with ecological services, SLR may adversely affect the livelihood of coastal populations and drive migration from rural into urban centers (Waha et al., 2017).

3.3. Opportunities

Population growth rate in the Red sea region is high and it is predicted that the population will nearly double within one generation (United Nations, 2017; Table 1).

The relatively sparsely populated Red Sea coast is about to change dramatically if urban development plans are to materialize: the mega-project Neom (amalgamation of "new" and arabic "mustaqbal = future") proposes to build a huge transnational city along 470 km of Saudi Arabian–Jordanian coast with a bridge access to Egypt. Five hundred billion US dollars were allocated to economically "fuel" this project, which is anticipated to be completed by 2030. The King Salman bin Abdulaziz bridge over the straits of Tiran, connecting Egypt and Saudi Arabia, allowing crossing of people and commodities is planned as part of the Neom project. This will also support Egypt's aspiration to repopulate the Sinai Peninsula, boosting diving tourism, which is already a major source of income to the region. As one of the hottest areas in the world, climate change will likely result in population migration to urban centers with deterioration of rural livelihood (Gemenne, 2011; Waha et al., 2017). Climate change and political instability in the Red Sea region are likely to inspire huge demographic and socioeconomic changes (Held, 2018), and challenge environmental security in one of the world's most precious natural assets. Socioeconomic prosperity often conflicts with environmental sustainability if proper planning and management strategies are not implemented.

The two most important economic activities around the Red Sea reefs are tourism and fisheries. In Egypt, the number of foreign tourists visiting coral reefs equals that of tourists visiting the pyramids in Giza, Luxor, etc. (Cesar, 2003). The Sinai Peninsula is attractive because of St Katherine Monastery and the coral reefs surrounding the peninsula (Hilmi et al., 2012). Coral reefs-based tourism is economically important along the Egyptian Red Sea with 90% of the tourism investment concentrated around the Gulf of Aqaba (Hilmi et al., 2018). In Eilat Israel, 141,000 tourists entered the Coral Beach nature reserve in 2017 and 500,000 visited the Underwater Observatory Park, the country's number one attraction park, highlighting the public's interest in beautiful reefs. Saudi Arabia is developing a Red Sea tourism project (beginning in 2019) in order to reduce its reliance on oil (oil sector represents 75% of budget revenues, 45% of GDP (gross domestic products), and 90% of export earnings), as it is expected to create 35,000 jobs and contribute 15 billion riyals to the GDP. The sovereign wealth fund will finance the project, which will cover 34,000 km^2 between Umluj and Al-Wajh and include 50 islands (https://www.bbc.com/news/world-middle-east-40795570). By its nature, tourism is economically desirable because it brings in foreign currencies, but it can also be harmful ecologically, destroying the attractiveness of the visited spots, which are a natural heritage (Shaalan, 2005). Zakai and Chadwick-Furman (2002) demonstrated that current rates of recreational diving in some reefs at Eilat are unsustainable. Examples from the Maldives suggest that resorts are not necessarily associated with reef degradation, but highlight the need of proper waste management and environmentally-friendly infrastructure to reduce the impact of resorts (Cowburn et al., 2018).

Total alkalinity and Aragonite saturation state (Ω_{arg}) in the Red Sea are relatively high and increasing northward (Fig. 3C). Over the past decades however, calcification rates as derived from coral cores indicate a decline in response to ocean warming as shown for the Great Barrier reef, the Caribbean, and also the central Red Sea (Bak et al., 2009; Cantin et al., 2010; Cooper et al., 2008). In the central and southern Red Sea, present-day data indicate reduced calcification rates of corals and calcifying crusts during summer when exposed to warmest temperatures of the year (Roik et al., 2016b; Sawall et al., 2015). While increasing temperatures are seemingly stressful for calcifiers, high A_T values (~2400 μmol kg^{-1}, (Metzl et al., 1989)) are putatively beneficial for carbonate accretion in the Red Sea (Tambutte et al., 2011). Availability of calcification budget data for Red Sea coral reefs is poor (Jones et al., 2015; Silverman et al., 2007) and most studies only report calcification rates (Cantin et al., 2010; Heiss, 1995; Roik et al., 2016a; Sawall et al., 2015). A recent study in the Red Sea (Roik et al., 2018) shows that A_T and Ω_{arg} are on average higher in comparison to other coral reef systems, such as the Great Barrier Reef (GBR; (Uthicke et al., 2014) or Puerto Rico (Gray et al., 2012)). This implies that Red Sea waters have a high buffering capacity with regard to ocean acidification, and may reach critically low Ω_{arg} levels for reef calcification at a later time point than other tropical coral reef locations. As a consequence, coral reefs in the Red Sea constitute a stark contrast to locations of low A_T and

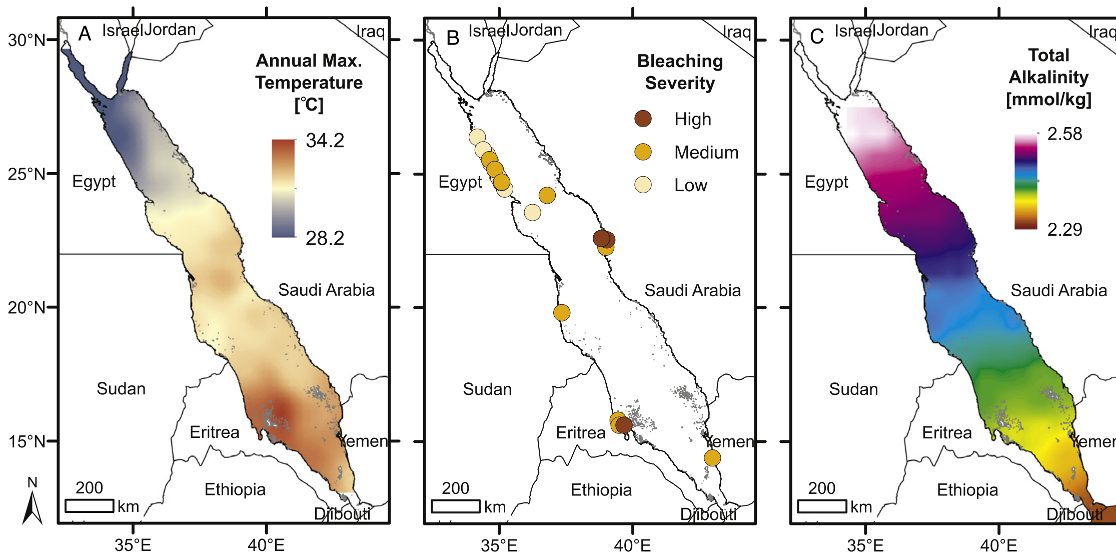

Fig. 3. Physico-chemical conditions and coral bleaching across the Red Sea. The annual maximum temperature (left map) shows the highest recorded temperature during the period of 1982–2015 (data taken from (Chaidez et al., 2017). Coral bleaching severity (middle map) illustrates the graphical distribution of coral bleaching events during the period from 1997–2012 (data taken from Osman et al., 2018). Total alkalinity (TA) is naturally high in the Red Sea and beneficial for reef accretion as it facilitates the precipitation of calcium carbonate to build coral skeletons, which comprise the structural foundation of coral reef ecosystems (data taken from https://odv.awi.de/data/ocean/global-alkanity-tco2/ (Schlitzer, 2018). All three maps support the notion that the northern Red Sea provides a refuge for corals as annual maximum temperature are lowest (A), total alkalinity is highest (C), and no severe bleaching is reported (thus far) (B). All data were downloaded from the respective sources and imported into ArcGIS (Esri, Redlands, CA, USA).

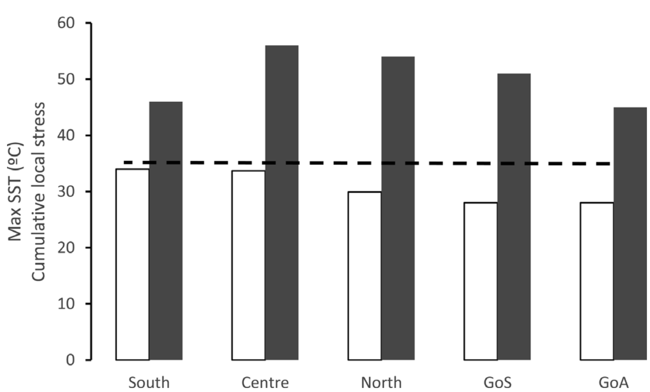

Fig. 4. Thermal stress in the southern Red Sea is already high (white bars show maximum monthly mean SST) crossing the expected bleaching threshold (dashed line) during hot summers, while the northern sections of the Red Sea including the Gulf of Suez and the Gulf of Aqaba are still far under that threshold, despite a rapid warming rate. In addition to global warming which poses immediate stress to southern sections, local stress (black bars, data taken from Table 2) is threatening reefs by reducing corals thermal resistance. To calculate the cumulative local stress, ranking of stressors in Table 2 were summed for each section. Different local stress received the same weight, although this may be incorrect. It should also be considered that interactions between certain local disturbances might result in synergistic effects.

Ω_a that are critically threatened by ocean acidification, such as the marginal coral habitats of Bermuda (Yeakel et al., 2015) or the eastern tropical Pacific, e.g. Galápagos and upwelling sites off Panama (Manzello et al., 2008). Interestingly, however, a recent study on carbonate budgets in central Red Sea reefs found overall reef growth in line with the global average, suggesting that A_T and Ω_{arg} do not translate to higher reef growth, possibly due to opposing environmental factors, such as high temperature (Roik et al., 2018). Since calcification rate along the Red Sea is primarily governed by temperature (Silverman et al., 2007), Southern and central Red Sea corals which live closer to their thermal maximum, are likely to decrease in growth rate (Cantin et al., 2010). A recent study report that coral reefs of the southern Red Sea show constant decline in calcification rate during the last couple of decades, suggesting these reefs are under severe stress (Steiner et al., 2018). Northern Red Sea reefs and particularly in the Gulf of Aqaba, which live far below their thermal maximum and in some cases sub-optimally (Krueger et al., 2017), show increasing growth rate with the warming trend (Heiss, 1995).

Thus, warming of the northern Red Sea may promote increased growth rates in reef-building corals, offsetting reduced coral calcification due to ocean acidification soon. At the same time, it is important to note that coral sensitivity to thermal stress may increase due to ocean acidification (Anthony et al., 2008) or other energetically costly environmental changes, which may require increased investment of resources in maintenance (Grottoli et al., 2017).

3.4. Threats

3.4.1. Reef-building corals and environmental change

Rapid rise in atmospheric carbon dioxide concentrations during the Anthropocene poses a severe threat to the existence of corals and consequently to the entire coral reef ecosystem (Hoegh-Guldberg, 1999). Since the start of the industrial revolution, approximately one third of released carbon dioxide has been absorbed by the ocean. The subsequent effect on the carbonate chemistry is a lowering of ocean pH, termed ocean acidification (Doney et al., 2009). In addition, carbon dioxide is a greenhouse gas. Consequently, global mean atmospheric temperature is rising at a rate faster than ever observed in the paleo-climate record. Since the air and the sea's surface are tightly linked, SST has also risen during the Anthropocene (IPCC 2014; (Raitsos et al., 2011)).

Elevated SST has been incited as the dominant cause of coral bleaching (Hoegh-Guldberg, 1999) and is now considered the main driver of global reef degradation (Hughes et al., 2017b). Coral bleaching is a process by which the density of algal symbiont cells or the chlorophyll pigments they harbor are reduced in the coral. Since photosynthates from the symbiont provide the coral animal with the significant majority of its energy intake (Muscatine, 1990), the coral will eventually die unless a rapid recovery is permitted via a decrease in temperature. The frequency of global coral bleaching is increasing (Heron et al., 2016). Reefs of the world experienced recently significant coral bleaching during three consecutive years (2014–2017) (Hughes et al., 2018, 2017a; Monroe et al., 2018).

The rate of SST warming in the Red Sea greatly exceeds the tropical average (Kleypas et al., 2008; Roik et al., 2016b). On average, in tropical waters where maximum sea surface temperature is < 29.5 °C, there has been an average warming of 0.2–0.4 °C between the periods 1950–1969 and 1987–2006 (Kleypas et al., 2008). In the Red Sea however, SST rose on average by 0.62 °C and by more than 1 °C in some parts of the central Red Sea in just two decades between 1985 and 2006 (Cantin et al., 2010; Raitsos et al., 2011); Fig. 3a). Despite this warming, bleaching, although severe in some sites, has only been observed in the southern (Yemen; (Kotb et al., 2004)) and the central Red Sea during 1998 (DeVantier et al., 2000; Furby et al., 2013; Riegl et al., 2013); (Rowlands et al., 2012) and 2016 (Monroe et al., 2018), in stark contrast to the widespread thermally induced mortality in many other regions during the same period (Donner et al., 2005; Eakin et al., 2010a,b; Heron et al., 2016); Fig. 3B). Nevertheless, calcification rates commonly highest in summer, are highest in spring in the central Red Sea, indicating that summer temperatures are past-optimal (Roik et al., 2016a), at least in the central Red Sea.

3.4.2. Local environmental stress in the Red Sea

The future of coral reefs in the Red Sea depends on rates of acidification and warming, but also on more local anthropogenic disturbances (Table 2 and Fig. 4). Human populations along the coasts of the Red Sea use the sea as a resource (fishing, transportation, bioactive materials, tourism, etc.), but often overexploit it or misuse it, resulting in compromised coral health and lower resistance to global disturbances (such as warming and acidification).

As a narrow and long sea, resulting in the coastline to water surface area/volume ratio being higher than in wide oceans, the land may have a high impact on the sea and its coral reefs. Furthermore, coral reefs of the Red Sea are mostly fringing reefs existing close to shore, exposing them to anthropogenic stressors. These stressors may adversely affect coral bleaching thresholds (Fabricius, 2005; Wooldridge, 2009), with onset of bleaching happening at a lower temperature. Land-associated sources of pollution in the Red Sea are composed of poorly or non-treated sewage discharge with cities and touristic centers being hotspots of sewage runoff, which results in eutrophication of the coastal waters (Gerges, 2002; Ziegler et al., 2016). Nutrients from sewage and/or mariculture, detergents, herbicides, and pesticides from public gardening and agricultural fields present reefs of the region with a major challenge. Mohamed et al. (2012) studied 9 sites along the northern Egyptian Red Sea, concluding that enhanced local anthropogenic stresses and increasing sea surface temperature due to global warming are likely the causes for the initiation and the persistence of coral diseases in the studied reefs.

4. Discussion and proposed solutions

The Red Sea is a source of wealth for the eight countries surrounding it and the livelihood of coastal populations around the Red Sea is highly dependent on healthy coral reefs. As a rich and highly diverse sea, it offers great opportunities for prosperity, but at the same time, it is under threat from global climate change as well as shore and marine associated human activities (Fig. 4). The eight countries around the Red Sea have at present a relatively low carbon footprint and accordingly a smaller-than-most influence on global carbon emissions (Table 1). Thus, when discussing human activity in proximity to the reefs, we should be aware of the global processes that occur in the background. Gladstone et al. (2013) identified direct impacts of coastal and marine tourism on the environment in the Red Sea, including the Gulf of Aqaba and Gulf of Suez, such as local pollution, resource depletion, habitat loss and conversion, habitat and wildlife disturbances, but also indirect impacts due to support infrastructure, disposal of waste, invasive species, and increase in human population. Local residents' behavior is sometimes very harmful to the reefs. For example, near Hurgada, residents make lampshades by inflating dried pufferfish for tourist souvenirs. As Yu (1994) pointed out, the overfishing of pufferfish leads to increased sea urchins, which damage the reefs by grazing on coral recruits and contributing to bioerosion. Sustainable use and development is key to secure the Red Sea coral reef resource for future generations. That said, we identified four types of challenges that should be considered when planning resource management in the Red Sea:

A. **Latitudinal-differentiated management solutions.** The wide latitudinal range from the Bab el Mandab straits to the Gulf of Suez and the Gulf of Aqaba entails strikingly different environmental conditions (climate, weather, seawater temperature, total alkalinity etc.). Therefore, solutions and management tools have to be latitudinally adjusted. For instance, maximum sea surface temperature (SST) in the northern Gulf of Aqaba equals the minimum SST in the southern Red Sea, revealing that stress on reef communities is different.

B. **Policy consistency along coastlines**. Difficulties in adopting the same management policies for different coastline lengths. Management of a 13 km coastline (such as the Israeli coast) is very different to managing 2000 km of coast (such as in Saudi Arabia). While management will likely remain at a country scale, guidelines and solutions in this paper are generally set according to latitudinal sections.

C. **Acting for the common good of the region.** Challenges in sustainable use of reef resources and management in the Red Sea stem also from the geopolitical situation and unrest. "Tragedy of the Commons" (Ostrom, 1999), where every country is acting independently according to its own self-interest may turn to be disastrous in the narrow Red Sea. Collaborative effort is essential to properly manage Red Sea resources. This can be achieved with the aid of a third party, a neutral country/organization, that will mediate regional environmental conflicts.

D. **Regulating uncontrolled urbanization**. The current greatest challenge for management planning is the urbanization plans for the region, which, if to materialize, will multiply population size a few folds within a relatively short time and increase the environmental pressure on the already frail status of coral reefs in this region.

Looking to the future, in this paper we identify the following solutions or actions that we recommend for the entire Red Sea, regardless of latitude, divided into three main categories: ecological, socioeconomic, and political.

4.1. Ecological solutions

There is an urgent need for the incrrease of scientific knowledge to be able to manage natural resources of the Red Sea. Closing knowledge gaps on coral resilience is crucial: the Red Sea harbors some of the most thermotolerant corals and we need to fully understand what the mechanism for this resilience is (Grottoli et al., 2017). Understanding this mechanism is of global importance, given the frail state of reefs worldwide. This will require work across the latitudinal range and knowledge exchange between different sections, and hence countries, of the Red Sea.

While the Red Sea hosts some of the most resilient reefs with regard to global threats (e.g., ocean warming and acidification), these reefs are not safe from local anthropogenic impacts (Table 2), and require measures to minimize local disturbance and removal of all hazards if we are to secure these reefs for future generations. One of the traditional ways to remove disturbances is to increase the numbers and sizes of marine protected areas (MPAs), but it has to be noted that pollution drifts long distances and so MPAs alone are not the (only) solution. It is also important to ensure that when MPAs are established they are in accord with international conservation standards, so they are meaningful spatial management measures (IUCN, 2018) and not just 'paper parks'.

Artisanal overfishing is widespread throughout the Red Sea. Regulations need to be put in place to monitor and regulate the catch, in particular during the reproductive season of key fish species.

A coral repository should be considered in the form of local and regional coral nurseries to preserve essential local genotypes and local coral species (primarily endemic, rare, and/or endangered species). Some reef species are highly dependent on the existence of other species. Where appropriate, propagating an endemic, key species means securing one or more, sometime many, other species.

Prepare the coral restoration "toolbox" for cases and the time, when they are needed (Rinkevich, 2015a). Coral restoration technologies should be developed for different reef systems (fringing, offshore, island) and for different purposes (mariculture, shore protection, nurseries for fish, reef complexity, hubs for coral reproduction use as stepping stones for coral connectivity and more). Given the large surface area of reefs in the region, even the methods of reseeding corals have to be carefully tested and developed. Furthermore, employment of ecological engineering approaches may enhance the acclimation and adaptation mechanisms of impacted corals. Ecological engineering is applied in order to reverse declines of biological diversity caused by coastal urbanization and habitat degradation. It has been demonstrated, however, that coral recruitment is sensitive to substrate texture, complexity, and mineralogy (Liversage and Chapman, 2018). Hence, sufficient knowledge is required before ecological engineering can be applied.

4.2. Socioeconomic solutions

Tourist and hospitality industry management: the northern Red Sea is a hub for tourism and it is predicted that other Red Sea sections will follow the same trend. As such, it is in the interest of the bordering nations to develop a sustainable region.

Collection of data for building a socioeconomic dataset/database: a centralized coordination center is required to allow better monitoring and implementation of conservation policies in the region.

Education: efforts should be put into place to educate the local people about the value of coral reef ecosystems with regard to their cultural, economic, and ecological value, and with regard to actions that can be done by single individuals. Part of this effort should be "Citizen Science", namely public involvement in monitoring and research of Red Sea related coral reef affairs. Tour operators should also educate the tourists. Close cooperation between local residents and foreigners may contribute to preventing reef degradation (Yu, 1994).

Capacity building: while countries bordering the Red Sea rely on many of its services, opportunities should be created that incentivize individuals that choose a career track in Marine Science.

Business opportunities on reef resources (blue technology): identify and develop sustainable use of Red Sea bioactive materials from reef organisms as novel tradable goods and services (Rinkevich, 2015b).

A more sustainable tourism: countries should rely more on tourism quality than quantity, and the private sector should pay attention to the protection of the reefs when they undertake large-scale projects (Hilmi et al., 2012). Hasler and Ott (2008) propose to reduce the number of divers per year to implement sustainable dive plans and educate both dive guides and divers in order to preserve the coral reefs. Hawkins and Roberts (1997) considers that it is possible to increase the carrying capacity of a given reef area by increasing the environmental awareness of divers (by short briefing before diving). Tratalos and Austin (2001) suggested to exclude untrained divers. Zakai and Chadwick-Furman (2002) recommend reef management measures to preserve the reefs in Eilat, such as limited number of divers, more educated and certificated, only led by guide divers, avoid natural coral reefs and prefer to dive in artificial reefs. Such a measure can be determined by science-based approaches similar to that proposed by Leujak and Ormond (2008a) for the Ras Um Sidd reef at Sharm El Sheikh and Ras Mohammed National Park. These authors correlated reef trampling frequencies to reef-flat damage and determined that the limit should be set at approximately 50 tramplers/m^2/yr. To avoid anchor damage, the Hurghada Environmental Protection and Conservation Association implemented a mooring system at all key dive sites in Egypt (PERSGA, 2010). In 1992, approximately 100 mooring buoys were installed. This local mooring project has evolved into the world's largest mooring system with over 1000 moorings installed and maintained throughout Hurghada, Safaga, and the southern Red Sea (http://www.hepca.org).

4.3. Political solutions

Considering the four components of the SWOT analysis (Fig. 1), we endorse the following policy solutions. First and foremost we emphasize the need for regional collaboration and management, which will consider the extensive latitudinal diversity along the Red Sea. The Red Sea human population is highly heterogeneous socioeconomically, multi-cultural, and has different economical aspirations. This should be considered when planning coastal management. Education, training, and capacity building is needed to narrow down gaps, allowing all people of the Red Sea region to sustainably use the Red Sea. We propose building a database and databank with cross-sectional and time series data sampled from various locations, so that researchers are able to analyze trends and have predictions to aid preservation of the reefs.

Regional collaboration and concerted efforts: as coral reefs worldwide are under threat from global and local stress, the northern Red Sea coral reef refuge deserves special protection measures. Even though Red Sea reefs are unique, at present there is only a single UNESCO world heritage site in the Red Sea (Sudan). Marine Protected Areas (MPAs) are not always adequately managed, and regional management is lacking (except for PERSGA, which does not include all 8 countries). The new Malta agreement (Coral Reef Life, Oct 2017) has yet to be signed by any Red Sea country.

Political solutions are key in the geopolitically complex Red Sea region. Since coral reefs do not recognize political borders and actions in one country's reef may influence reefs in another country, coordination is a condition for proper management. It is important to strengthen regional monitoring, to accelerate distribution of knowledge, and for the neighboring countries and the international community to endorse collaborative research and protection of this remarkable natural resource.

The choice of decision-makers: governmental institutions should employ knowledgeable experts or rely on consultancy reports about the Red Sea.

Planning and building education should be on the agenda of ministries (Gohar and Kondolf, 2016).

While we call to narrow knowledge gaps, reduce uncertainty, and educate for sustainable development, "shocks and discontinuities" should be considered. These may influence each of the sections above (ecological, socioeconomic, and political): the Red Sea is part of the Syrian–African fault, thus the area is active tectonically. A major earthquake and seabed changes may result in vast morphological and even chemical changes in the Red Sea. Ecological disasters such as major oil spills or chemical spills might detrimentally affect the Red Sea environment for many years due to their relatively long residence time, which may exceed 200 years (Hoepner and Lattemann, 2003). Crisis in the world's economy may lead to a regional economic shock and change in markets/priorities. Changes from oil economy to tourism, from fisheries to shipping and ports industry, or changes to advanced technology may lead to dramatic changes in the way the Red Sea is perceived and the way reefs are cared for.

Finally, political unrest and military activity are the Red Sea environment worst scenarios, as they diminish all coordination, promoting a "Tragedy of the Commons" scenario.

5. Conclusion: Latitudinal differential solutions

The range of abiotic conditions along the Red Sea, the anthropogenic activities, as well as the socioeconomic differences from south to north determine the appropriate solution(s) for each Red Sea section. The greatest hindrances to best management in the southern section are the lack of proper monitoring, knowledge, and education. Improving these limitations is likely to lead to mitigation of some anthropogenic disturbances such as overfishing, oil spills, and sewage runoff. Sustainable development and proper use of reef resources will increase resilience to thermal stress of these reefs that already experience harsh conditions during summer. The middle section of the Red Sea is also suffering high temperature fluctuations during summer, as well as overfishing, pollution, and deep-sea mining. This is the most densely populated section in the Red Sea. This section also hosts the only Red Sea UNESCO world heritage site in Sudan. While already rapidly developing, there are plans for major urbanization along the eastern coast of the Red Sea. It is imperative to reduce the pressure on the reefs in this section, while planning future development in a sustainable, reef-friendly manner.

The northern section of the Red Sea hosts some of the most resilient reef corals and is not as developed and populated as the middle section on the eastern side. The western bank of this section operates a massive reef tourism industry and includes numerous hotels, marinas, and ports. This area suffers from oil pollution and untreated sewage. Big investments in monitoring, regulation, and enforcement are needed in order to secure these reefs as world-class diving and reef attraction sites.

The Gulf of Suez hosts some of the richest reefs in the Red Sea. Towards the northwest, the environmental conditions as well as heavy maritime traffic, oil terminals, sewage, light and acoustic pollution, make conditions unfavorable for coral reefs. Monitoring, regulating, and enforcing clean water is crucial for this section.

The Gulf of Aqaba (GoA) is unique globally for its high diversity, but mainly because at the present it is one of the coral reef refuges from climate change and ocean acidification. As such, it should be highlighted for protection. The GoA is the most urbanized and developed section and therefore puts some of the most precious reefs at immediate risk. The high resistance to elevated temperature (Krueger et al., 2017) is compromised when corals are exposed to local stress (Hall et al., 2018). The preferable way to secure the reefs of the northern Red Sea for future generations is to scientifically study and manage this natural resource on a regional scale. This requires international collaboration, coordination, and planning.

Regardless the various latitudinal differential solutions, there is a need to develop the coral restoration "toolbox" for cases and the time it will be needed. Global climate change differentially affects regional ecosystems, causing unprecedented degradation to coral reefs. Following the above, restoration activities should evaluate novel considerations, such as climate change scenarios, focusing on adaptation strategies that had not been considered in past reef management settings (Rinkevich, 2014). The developed "toolbox" for reef restoration may include genetic considerations and the employment of ecological engineering approaches. To support these endeavors there is a need to identify the populations and genotypes of reef-building corals that can withstand and adapt or acclimatize to recurrent bleaching events.

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